International Journal of Mechanical and Production Engineering Research and Development (IJMPERD)
ISSN (P): 2249–6890; ISSN (E): 2249–8001
Vol. 11, Issue 5, Oct 2021, 155–178
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PRINCIPLES FOR ACHIEVING ENERGY SECURITY IN DEVELOPING COUNTRIES

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ABSTRACT

Fossil fuel energy sources being carbon intensive have the disadvantage of accelerating climate change as well as being non-renewable and, by implication, limited in supply. This poses a threat to the energy security of a country, especially if carbon intensive energy sources serve as the mainstream energy source of a country. Mitigating climate change is a global imperative and involves a fundamental shift from primarily fossil fuel energy sources to alternative, less carbon intensive, energy sources. For many countries this may mean changing energy sources long before the fossil fuel energy reserves are depleted. Changing energy sources means changing power generation technology and infrastructure to utilize new energy sources which requires finances as well as appropriate changes in legislation, policy and other instruments that influence markets to allow this development to progress, especially where energy generation is a closed market, as found in South Africa. Technology change is usually a complex challenge in developing countries as such countries need to overcome the financial barriers associated with new installations as well as the human capacity barriers in terms of skills in the new technology areas. Added to this is the task of ensuring that the energy sources are suited to the operating environment they serve. This paper presents the principles for achieving energy security in developing countries through exploring the range of energy sources available for a developing country and what energy mix may be suitable, bearing in mind the financial and technological challenges and the nature of the operating environment.

KEYWORDS: Low Carbon Energy Mix, Energy Security, Renewable Energy, Climate Change Mitigation, Wind Energy, Geothermal Energy, Solar Energy, Tidal Energy & Natural Gas Power Plants

Received: Jul 12, 2021; **Accepted**: Aug 02, 2021; **Published**: Sep 23, 2021; **Paper Id**: IJMPERDOCT202111

Original Article

1. INTRODUCTION

Developing countries face unique challenges regarding the road to achieving energy security in the context of the global warming crisis. Most of these challenges are related to the lack of financial resources and the lack of the necessary skills and expertise to embark on new technologies and strategies to achieve energy security. Typically, developed countries have the skillsets, finance and established markets for technologies that are key in achieving energy security. Developing countries usually have a single primary fuel source and dominating technology for energy production and orientate their efforts and budgets to ensure that this energy production base is increased for greater access to energy. Designs and technologies are targeted to be low-cost and simple so as to produce energy quickly and conveniently in abundance for stimulation of economic growth. Developed countries, however, do not have lack of energy access to the same degree that developing countries have. Typically, energy access has been achieved a while back and with modifications to designs, energy efficiency and other techniques of cost efficiency, developed counties ensure that they have well-developed and competitive energy sector with supporting commercial markets. The oil crisis over the last century has also played a role in their quest for and establishment of

alternative energy sources such as renewable energy [1]. It will be easier for developing countries to transition to energy security from an infrastructure perspective as they do not need to replace or "tear down" existing infrastructure and technologies to shift to less-carbon intensive energy technologies and infrastructure [1].

The task of shifting away from tradition fossil fuel energy sources and power generation infrastructure can be daunting for businesses and organizations in developing countries as they face business risks related to unfamiliar energy sources and associated technologies. In a developing country, this could mean facing risks of businesses not being market competitive, and ineffective in delivering services and producing products, all of which can result in declining profit margins. This paper presents principles and approaches to ensuring that energy security is realized in developing countries.

2. PRINCIPLES FOR ENSURING ENERGY SECURITY IN DEVELOPING COUNTRIES

A typical developing country like South Africa is currently facing challenges with energy access in that energy demand has exceeded the capacity of Eskom, the country's state-owned electricity provider. This has resulted in periodic load shedding since 2008. No plans have been finalized for new energy generation. This approach is not sustainable for the country, and this is evident in the legislation being introduced to allow the market of energy generation via wind and solar PV to be open to the private sector, as well as offering incentives for energy efficient lighting and water heating technologies in the decade following the first rolling blackouts.

South Africa's aging coal-fired power stations are being operated way beyond their useful lifespans with much needed maintenance being overdue on power generation, transmission and distribution infrastructure, indicating that this is only the beginning of the challenges faced by South Africa when it comes to energy generation. Climate change and the global efforts to move away from coal, which is the primary energy source of the country, paints a foreboding picture of developing countries' energy security. Any institution or business in South Africa using energy generated by Eskom will face challenges with energy security as all the issues faced by Eskom will be transferred to the institutions it serves. The risk of energy security can be decoupled if a business or site reduces both demand for energy and dependence on Eskom. In [2], [3], [4] and [5] reduction in energy demand through energy efficiency and energy conservation has been systematically addressed. Using these sources as a basis for the energy security solution of decoupling from Eskom, the following three principles are presented to achieving energy security in a developing country like South Africa with characteristic reliance on fossil fuel sources for energy requirements.

2.1 Principle 1: Understand the Site's Available Resources

The four factors of production as outlined in [6] tell us that land, resources, labour and capital are key ingredients for production. It is important that we view all land that is in control of and under ownership of an organization as a commercial resource. The naturally occurring features of the land's resources and the daily natural endowments must be viewed from the point of its commercial value and its ability to provide for the needs of the site.

Principle 1: Ascertain the energy generation potential of the site, i.e., what is the:

- **Theoretical energy potential of the site;**
- **Available energy potential by applying the commercially available technologies; and**
- **Real energy generation potential considering the spatial and other demands required for energy generation.**

Figure 1 shows the flowchart of the process for Principle 1 and the following sections give the definitions of the theoretical energy potential, the available energy potential and the real energy generation potential.

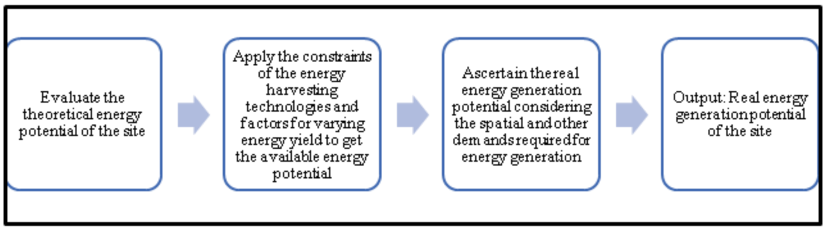


Figure 1: Process Flow for Ascertaining the Energy Generation Potential of a Site.

A. Theoretical Energy Potential

The energy generation potential of a site includes the renewable energy it experiences such as solar irradiation, wind energy, rainfall for the regeneration of hydro sources and basins, tidal energy for coastal areas, the geothermal energy available due to the site's location and landscape. The energy generation potential should also include the less-carbon intensive energy sources which can be considered as an alternative energy source, such as natural gas networks, hydrogen fuel availability, etc. as per the networks established within the geographical region. The energy generation potential also includes the energy sources that occur from business activities such as sewerage and waste streams. Fig. 2 indicates the typical theoretical energy potential energy sources for South Africa.

Solar irradiation over South Africa is abundant and can be used to generate electricity as well as thermal energy for various processes. Wind energy is abundant in the coastal areas of South Africa and its energy can be used to generate electricity and its motion can also be used directly. Tidal energy can be harvested to generate electricity and the opportunity for tidal energy is abundant as the south, west and east sides of the country are coastal. Geothermal energy can be used for heating and cooling requirements. Hydro energy can be used to generate electricity. The country has natural gas networks in certain regions which could serve as an alternate fuel source (to the predominant coal resource) for energy. As a product of most human activity, solid waste and sewerage that would usually cause a challenge could be used as a fuel source. Thus total theoretical energy potential can be given as represented in Equation (1).

$$Total\ Theoretical\ Energy\ Potential = \sum Renewable\ energy\ potential + \sum Energy\ potential\ from\ human\ and\ industrial\ activity + \sum Energy\ potential\ from\ alternative\ less\ carbon\ intensive\ energy\ sources \quad \text{Equation (1)}$$

Where: energy potential is given in kWh/m^2 and in the case of waste to energy, it is given in kWh/m^3.

Solar energy potential measured across South Africa is classified into two main types according to how it is harvested and used, i.e., global horizontal irradiation (GHI) and direct normal irradiation (DNI). When intending to produce electricity from solar energy the GHI is considered, and when thermal energy is the intention, the DNI is considered. Figure 3 and figure. 4 show the GHI and DNI potential of South Africa.

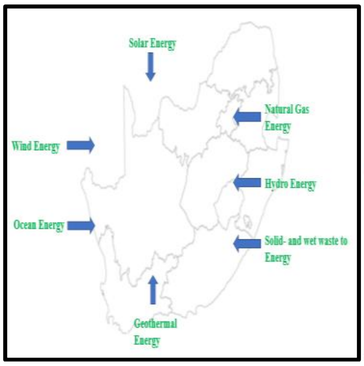


Figure 2: Energy sources available for South Africa [7].

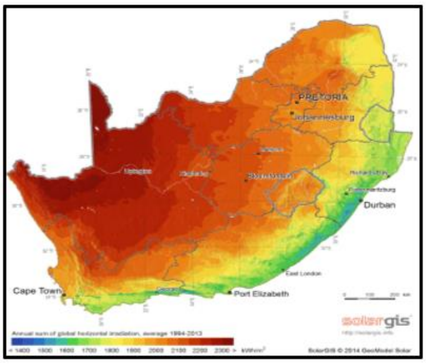


Figure 3: Global Horizontal Irradiation [8]

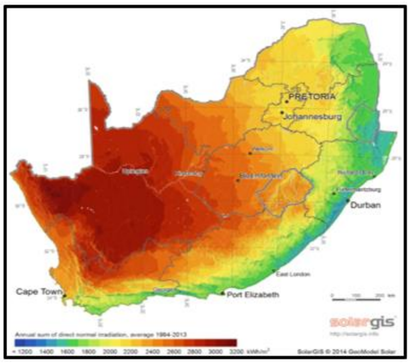


Figure 4: Direct Normal Irradiation [9].

Figure 3 and figure 4 show that the country of South Africa is generally abundant in solar energy and more abundant in its north westerly parts. The wind energy potential of South Africa can be seen in figure 5.

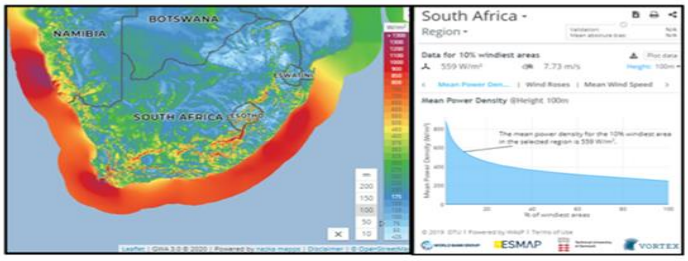


Figure 5: Wind energy potential for South Africa [10].

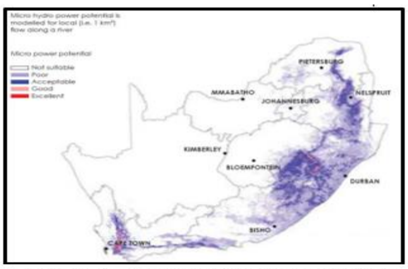


Figure 6: Micro-hydro power potential [11].

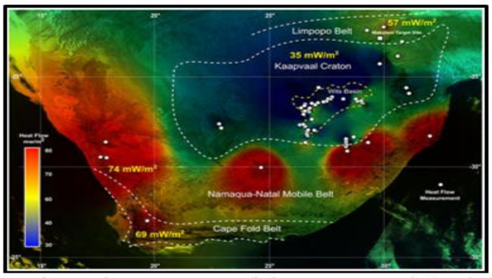


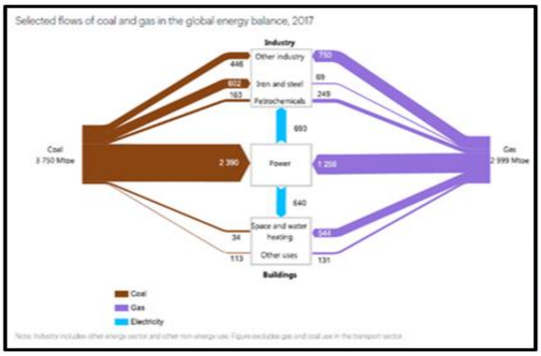
Figure 7: Geothermal energy potential zones around South Africa [13].

South Africa has a strong wind energy potential in the coastal region of the country and a generally wind-rich band between the coast and midland of the country which is about 7.7 m/s at 100 m above ground level with potential mean energy generation of about 560 W/m^2. The micro-hydro power potential for South Africa seen in Fig. 6 shows that the country has a strong potential on its east coast (from the north to the south) and on the south-west coast. Detailed assessment of the spatial distribution of wave power off the southwest coast has been recently conducted. It was found that the average deep-sea resource range from 33 kW/m to 41 kW/m [12]. Geothermal energy potential in South Africa can be seen in figure 7.

The inland area of South Africa shows an extremely low geothermal energy potential and the coastal areas indicate a much higher geothermal energy potential. One of the well-known geothermal installations in South Africa is the Western Cape's Hotel Verde geothermal heat sink serving the hotel's HVAC system, saving on water and energy. This installation does not utilize geothermal resources for heat, but rather, the opposite; it uses the ground as a heat exchange medium to decrease the temperature of the condenser water of the HVAC systems. Traditionally, cooling towers using

significant amounts of water and electricity are used to achieve this decrease in temperature.

A cleaner and greener alternative to coal-generated electricity and heat is the use of natural gas. Globally, this source of energy has been adopted as a solution to reducing carbon emissions [14]. Figure 8 shows that gas is now going head-to head with coal in power and in industry. South Africa has an established natural gas supply and infrastructure, as illustrated in figure 9. South Africa's gas supply is primarily from Mozambique, through the ROMPCO pipeline (figure 9).



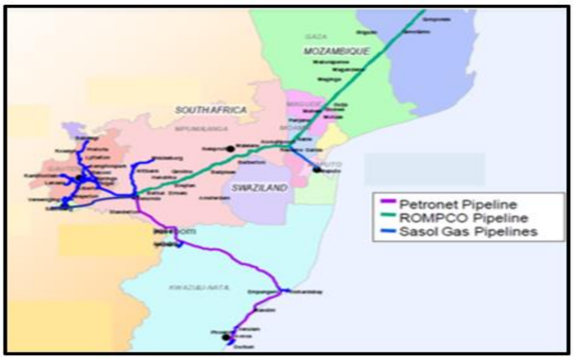


Figure 8: Coal Versus Natural Gas as per the Global Energy Balance in 2017 [14].

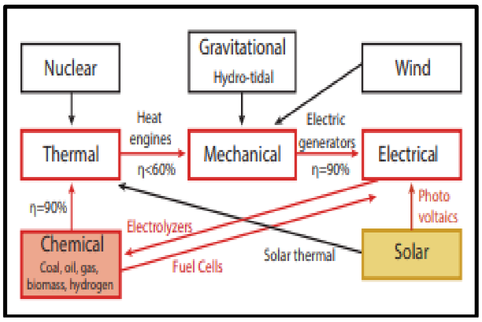
Figure 9: Main gas Pipelines within South Africa [15].

The major pipelines are the ROMPCO pipeline, Lilly pipeline and Sasol pipelines. The ROMPCO pipeline is 865 km long originating from Temane in Mozambique to Secunda in South Africa and is jointly owned by Sasol, the Mozambique government and the South African government. The Lilly pipeline is owned by Transnet and is 600 km long from Secunda to KwaZulu-Natal. Sasol owns several gas pipelines originating in Secunda and reaching destinations such as Gauteng, Ekurhuleni, Pretoria, Sasolburg and Emalahleni [15].

The energy potential of renewable energy, waste to energy and alternative fuel for energy must be harvested and converted to usable energy, whether this is heat, electricity, kinetic energy or any other type of energy that can be used to satisfy energy need.

B. Available Energy Potential

The available energy potential in this context is the amount of energy available to be used when one considers the capability of the commercial energy conversion technologies. Solar energy, wind energy, tidal energy, geothermal energy, hydro energy, natural gas and other sources of energy must be harnessed or converted into useful energy. Figure 10 shows various energy sources and how we utilize them. The available energy potential is thus represented by Equation (2).



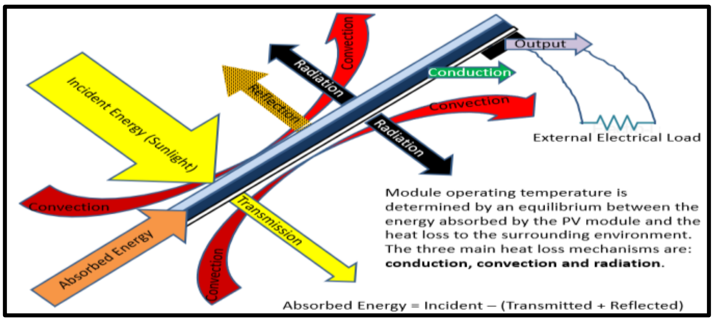


Figure 10: The Different Energy Carriers and how we Utilize them [16].

Figure 11: Solar PV Energy Harvested from Solar PV Module Technology and Inevitable Losses [17].

$$Total\ Available\ Energy\ Potential = \sum(Theoretical\ Energy\ Potential\ \times \eta_{energy\ harvesting\ technology})$$
………………………………………….. .Equation(2)

Thus, the “Total Available Energy Potential” considering Equation 2 in the context of the Equation (1) can be found in Equation (3).

$$Total\ Available\ Energy\ Potential = \sum\left(Renewable\ energy\ potential \times \eta_{technology}\right) + \sum\left(Energy\ potential\ from\ human\ and\ industrial\ activity \times \eta_{technology}\right) + \sum(Energy\ potential\ from\ alternative\ less\ carbon\ intensive\ energy\ sources \times \eta_{technology})$$
………………………………………………………………………… Equation (3)

Where: available energy potential is given in kWh/m^2 and in the case of waste to energy, it is given in kWh/m^3.

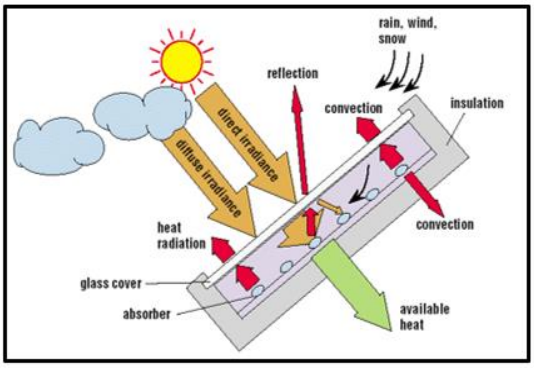
The chemical energy stored in fossil fuels is converted to usable forms of energy via heat by burning, with an efficiency of about 90 %. Using heat engines, thermal energy can be converted into mechanical energy. Heat engines have a conversion efficiency of up to 60 %. Their efficiency is ultimately limited by the Carnot efficiency limit. Mechanical energy can be converted into electricity using electric generators with an efficiency of up to 99 %. Most of the world’s electricity is generated with a turbo generator that is connected to a steam turbine, where coal is the major energy source. In the process of making electricity out of fossil fuels at least 50 % of the initial available chemical energy is lost in the various conversion steps. In nuclear power plants, energy is released as heat during nuclear fission reactions. With the heat steam is generated that drives a steam turbine and subsequently an electric generator, just as in most fossil fuel power plants [16].

Although solar energy falling on South Africa may be abundant, the energy that is able to be converted to electricity and heat is limited to the capacity that can be harvested with available commercial technologies. Energy losses, although they can be minimized through innovative design and smart materials, are inevitable, as illustrated in Fig. 11. Fig. 11 shows a full solar PV module where the solar PV cells are contained within a housing and installed with the electrical circuit that will carry away the electricity generated by the solar PV cells to the end user. Added to the losses represented in Fig. 11 is the capability of solar PV material to convert solar irradiation into electricity. The absorbed energy is the remainder of the incident energy after the transmitted and reflected energies are subtracted. The efficiency of the solar PV cell varies, depending on the photovoltaic material and the electrical design. The most commonly adopted and best trade-off for efficiency and cost solar PV technology is the multi-crystalline cell which is about 23 % efficient [18]. This efficiency is quite low relative to traditional fossil fuel power generation which is upwards of 70 %. This 23 % is further reduced when the cell is used in a power generation module which includes electrical cells. Solar PV technology is also susceptible to high temperatures and soiling which further decreases its efficiency, and this may result in a final efficiency of around 15 % to 17 %, on top of which which age plays a role with an annual decrease of about 0.5 % to 0.8 % over the 20-year useful lifespan of the solar PV technology. There is a theoretical limit for p-n single junction cell called the “Shockley-Queiser” limit (Equation (4)) for maximum solar cell conversion efficiency, and this is 33.7 % [17].

$$\eta(t) = \eta_L[1 - \exp\left[\frac{a_0 - a}{c}\right]] \quad \text{Equation (4)}$$

Where: η(t) is the time dependant efficiency; η_L is efficiency limit; a_0 is start year; a is calendar year; c is the development time

Using solar thermal energy to produce hot water also comes with many losses and unavoidable efficiencies, regardless of which solar thermal collector technology is adopted. Figure 12 shows the energy losses from a flat plate solar thermal collector which is a series of pipes contained in a rectangular containment insulated on all sides and optimized to attract and retain heat except for the top which is typically covered with glass to allow sunlight in. From figure 12 above one can see that there are reflective, convection, and radiation losses, through the top glass cover, but the back and sides are insulated to prevent significant heat losses from there. Various configurations of solar thermal collectors exist. Another popular and more efficient solar thermal collector is the evacuated tube solar collector that consists of a heat pipe contained within a vacuum to reduce the thermal losses that occur with flat plate collectors. Figure 13 shows the configuration of an evacuated tube solar thermal collector with emphasis on the containment of much of the thermal losses compared to the flat plate solar thermal collector.



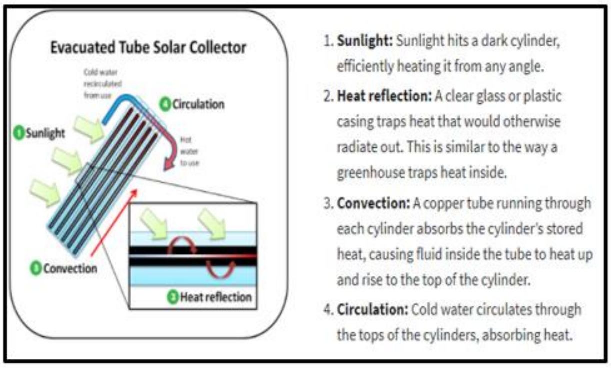


Figure 12: Depiction of Energy Flows for a Solar Thermal Flat Plate Collector [19]. **Figure 13: Evacuated Tube Solar Thermal Collectors [20].**

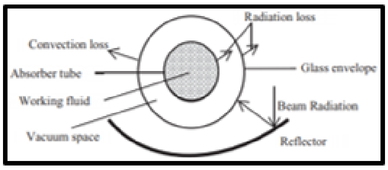


Figure 14: Configuration and energy losses of the parabolic trough collector system [21].

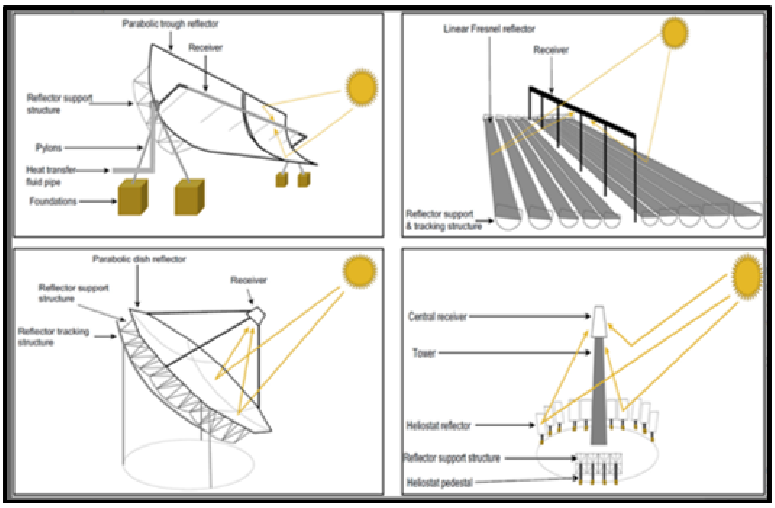


Figure 15: Current concentrated solar power technologies (CSP) [22].

Although much of the heat is trapped inside the heat pipe contained in the vacuum, there are optical losses such as reflection and convective and radiative losses which are relatively negligible when compared to flat plate collectors. Most of these collectors produce hot water and can be used for water heating purposes, as well as input for industrial and engineering processes. Equation (5) expresses the energy harvested by the collector with losses.

$$\dot{q_{coll}} = F_R(\tau\alpha)G - F_R U_L \Delta T \qquad \text{Equation (5)}$$

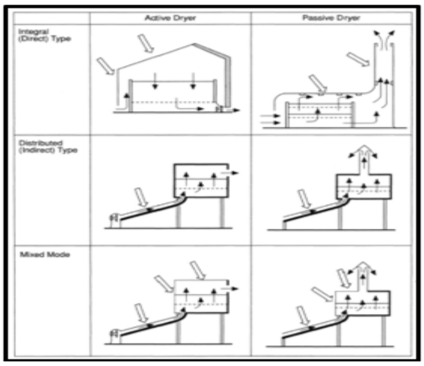
Where: $\dot{q_{coll}}$ = the energy collected per unit area per unit time (W/m^2)

- F_R = collector's heat removal factor
- τ = the transmittance of the cover
- α = shortwave absorptivity of the absorber
- G = global incident solar radiation on the collector (W/m^2)
- U_L = overall heat loss coefficient for the collector (W/m^{2}K)
- ΔT = temperature differential between the working fluid entering the collectors and outside (K)

Another way of using solar thermal energy is to produce steam via concentrated solar thermal collectors. The intention is to use the DNI (shown in Figure 4) to concentrate solar irradiation, resulting in the very high temperatures needed for the production of steam. Figure 14 shows the typical losses associated with the receiver of a parabolic trough collector. Figure 15 shows the various concentrating power technologies. Soiling plays a significant role in the efficiency of the CSP technologies.

The steam produced using concentrated solar power is usually coupled with a turbine and generator to produce electricity. Solar energy can also be used for drying agricultural produce. In this technology, heated air is used directly to dry agricultural produce.

In solar drying, solar energy is used as either the sole or a supplemental source of heat; air flow can be generated by either forced or natural convection. The heating procedure could involve the passage of preheated air through the product, by directly exposing the product to solar radiation or a combination of both. Figure 16 shows generic solar dyers. Figure 17 shows energy losses (reflective and conductive) associated with indirect solar dryers.



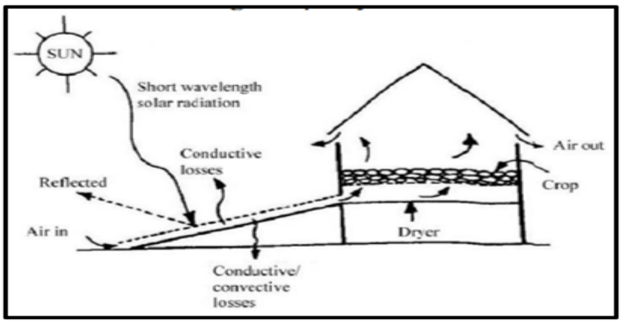


Figure 16: Configurations of Solar Dryers [23]. Figure 17: Energy Losses - Typical Indirect Solar Dryer [23].

Wind turbines have limitations on the amount of wind that can be harvested for energy production. The wind energy potential equation shows the maximum conversion efficiency of wind turbines. This maximum conversion efficiency is called the Betz Limit. This is expressed in Equation (6).

Wind Energy Potential: $P = \frac{1}{2}\rho A V^3 C_p$ Equation (6)

- P = Power available
- ρ = air density = 1,23 kg/m^2
- V = wind speed
- A = πr^2 (r = length of blade)
- C_p = 0,59 (Betz Limit) which is the maximum conversion efficiency of a wind turbine

The Betz limit is not static, C_p changes with wind speed and blade tip speed, given by Equation (7).

$C_p = \frac{blade\ tip\ speed}{wind\ speed}$ Equation (7)

(C_p needs to be looked at based on wind speeds)

Turbines need to be designed for optimal performance and reliability in whatever weather conditions they may face throughout their lifetimes, be it a gentle breeze on a low-lying plain or a raging offshore storm. Before deciding to build a wind turbine at a particular site, there are a few critical questions a developer needs to answer, such as the average annual wind speed in the intended location, what are the extreme gusts that can occur within a 50-year period, and how turbulent is the wind at the intended site. The three dimensions of wind speed, extreme gusts, and turbulence encompass the wind class of a wind turbine. The International Electrotechnical Commission (IEC) sets international standards for the wind speeds each wind class must withstand, as seen in the Table 1 [24].

Table 1: IEC Wind Classes [24]

	I (High Wind)	II (Medium Wind)	III (Low Wind)	IV (Very Low Wind)
Reference Wind Speed	50 m/s	42.5 m/s	37.5 m/s	30 m/s
Annual Average Wind Speed (Max)	10 m/s	8.5 m/s	7.5 m/s	6 m/s
50-year Return Gust	70 m/s	59,5 m/s	52.5 m/s	42 m/s
1-year Return Gust	52.5 m/s	44.6 m/s	39.4 m/s	31.5 m/s

These wind speeds occur at different heights above ground level and sea level. Wind potential changes and generally increases for all areas across South Africa with height above the ground.

Geothermal energy, whether used as a heat sink or for heat extraction, depends on the temperature of the ground and is governed by heat exchange principles and laws, as per Equation (8).

$Q = mC_p\Delta T$ Equation (8)

For geothermal heat sinks or heat extraction, Equation (8) can be rewritten to show that the temperature of the ground and the heat exchange working fluid is the efficiency at which the energy source operates, as per Equation (9). A

positive result shows that there is heat extraction and a negative result shows a heat sink.

$$Q_{geothermal} = mC_p(T_{ground} - T_{working\ fluid}) \quad \text{Equation (9)}$$

This implies that ground temperature is key to the geothermal loop's heat extraction and this is reflected in geothermal commercial market technologies (Fig. 18). Ground soil conditions are thus a key component that must be investigated and characterized when designing geothermal heat sinks or heat extraction. Ground temperature also varies with the weather up to 8 m to 9 m below the ground surface [25]. Another factor when designing geothermal heat exchange loops is to take into account that the ground temperature profile will change during the operation of the geothermal energy system, both in the long term and the short term. The short-term temperature profile will change in accordance with the daily heat exchange loads. This will be reflected in the coefficient of performance (COP) as per Equation (10). The COP equation for the heat pump graph in Fig. 19 is as follows:

$$COP_{geothermal\ heat\ pump} = \frac{Q_{geothermal}}{P_{electric\ of\ compressor}} \quad \text{Equation (10)}$$

As $Q_{geothermal}$ decreases, the COP of the geothermal heat pump decreases. In figure 19, t_u is the working fluid temperature and t_s is the temperature of the source which is the ground temperature in this case.

Length of collector probe (m)	3.0m	5.0m	10.5m
Extraction power (W)*	460 - 690	760 - 1,140	1,600 - 2,400

* depending on the soil structure and conditions

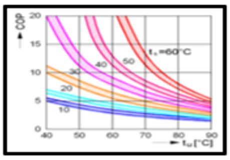


Figure 18: Limitations of Geothermal Heat Extraction [25].

Figure 19: Efficiency Variation - Geothermal Heat Pumps [26].

Similarly, with other power generation technologies, the same can be established. Table 2 shows the efficiency of gas turbine and spark ignition engine technologies. Performance is reduced at different altitudes above sea level and ambient temperatures.

Table 2: Efficiency of Gas Spark Ignition Engine - Typical Performance Characteristics [27].

Cost & Performance Characteristics	**System**				
	1	**2**	**3**	**4**	**5**
Baseload electric capacity (kW)	100	633	1121	3326	9341
Total installed cost in 2013 ($/kW)	2900	2837	2366	1801	1433
Form of recovered heat	H_2O	H_2O	H_2O	H_2O	H_2O, steam
Total efficiency (%)	80.0	78.9	78.4	78.3	76.5
Thermal output/Fuel input (%)	53.0	44.4	41.6	37.9	35.0
Power/Heat Ratio	0.51	0.78	0.89	1.06	1.19

Hydroelectric power generation, whether via rivers or the ocean, rely on potential energy and kinetic energy to generate electrical energy. Equation (11) and Equation (12) give the potential energy and kinetic energy equations, respectively.

Potential energy in hydroelectric generators: $P_{hydroelectric\ (potential)} = \rho g h Q \eta$ Equation (11)

Where: $P_{hydroelectric\ (potential)}$ = generated power (W)

- ρ = density of the water (kg/m^3)
- g = acceleration due to gravity (m/s^2)
- h = head of water (m)
- Q = volume of water flowing per second (m^3/s)
- η = efficiency of the turbine

Kinetic energy in hydroelectric generators: $P_{hydroelectric\ (kinetic)} = \frac{1}{2}\eta\rho A v^3$ Equation (12)

Where: $P_{hydroelectric\ (kinetic)}$ = generated power (W)

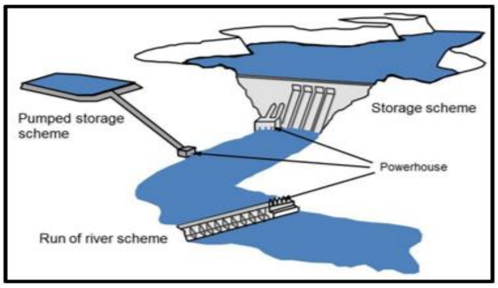
- η = efficiency of the turbine
- ρ = density of the water (kg/m^3)
- A = swept area of the turbine blades (m^2)
- v = velocity of the water flow (m/s)

If we use Bernoulli's equation: $v = \sqrt{2gh}$ Equation (13)

Making "h" the subject, $h = \frac{v^2}{2g}$ Equation (14)

Substituting in Equation (11), we will get Equation (12). If the head or pressure drop is known but not the velocity, use Equation (11). If the velocity is known neglect the head and use Equation (12).

There are three types of hydropower schemes, namely storage scheme, pumped storage hydropower (PSH) or scheme, and run-of-the-river scheme. These can be seen in figure 20. A typical PSH facility layout is shown in figure 21.



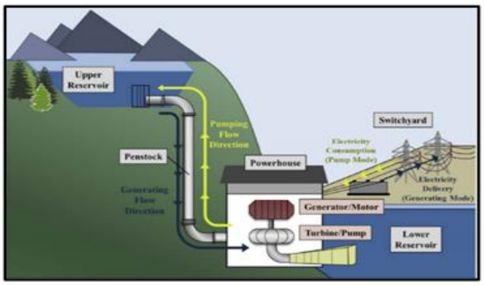


Figure 20: Illustration of the Main Types of Hydropower

Figure 21: Typical Pumped Storage Hydropower Facility Schemes [28]. Layout [29].

The majority of technologies harnessing ocean energy work on the same principles. Harnessing the energy from open-ocean currents requires the use of turbine-driven generators anchored in place in the current stream. Large turbine blades are driven by the moving water, just as windmill blades are moved by the wind. These blades can be used to turn the generators and to harness the energy of the water flow.

Tidal barrages, undersea tidal turbines – like wind turbines but driven by the sea – and a variety of machines harnessing undersea currents are under development. Unlike wind and waves, tidal currents are entirely predictable. Tidal

energy can be exploited in two ways:

- By building semi-permeable barrages across estuaries with a high tidal range, similar to run-of-the-river scheme and storage schemes (Figure. 20)
- By harnessing offshore tidal streams (Figure. 22)

Barrages allow tidal waters to fill an estuary via sluices and to empty through turbines. Tidal streams can be harnessed using offshore underwater devices similar to wind turbines.

Ocean thermal energy conversion (OTEC) uses temperature differences within the ocean to operate similar to the evaporator and condenser of an air conditioning system. There are three potential types of OTEC power plants: closed cycle (Figure. 23), open cycle (Figure. 24) and hybrid systems. Open-cycle OTEC systems exploit the fact that water boils at temperatures below its normal boiling point when it is under lower than normal pressures. Open cycle systems convert warm surface waters into steam in a partial vacuum, and then use this steam to drive a turbine connected to an electrical generator. Cold water piped up from deep below the ocean’s surface condenses the steam. Unlike the initial ocean water, the condensed steam is desalinated which may be used for drinking or irrigation. Closed cycle OTEC systems use warm surface waters passed through a heat exchanger to boil a working fluid, such as ammonia or a chlorofluorocarbon, which has a low boiling point. The vapour given off is passed through a turbine producing electricity. Cold deep ocean water is then used to condense the working fluid and it is returned to the heat exchanger to repeat the cycle. [31]

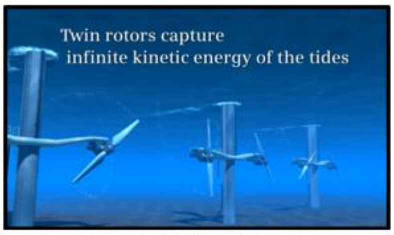
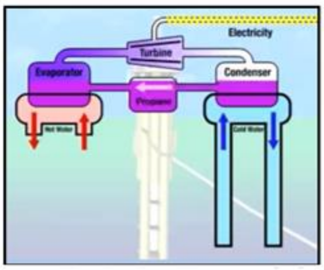


Figure 22: Harnessing offshore tidal streams [30].



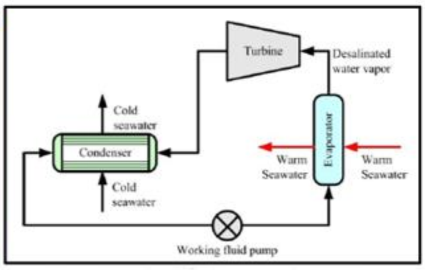


Figure 23: Closed cycle OTEC system [32]. **Figure 24:** Simplified open-cycle OTEC system [33].

The OTEC system relies on basic relationships between pressure (P), temperature (T) and volume (V) of an ideal fluid, as per Equation (15) [33]

$$\frac{pV}{T} = nR = constant \qquad \text{Equation (15)}$$

Where: R = the ideal gas constant

- n = the amount of substance

In OTEC systems, the difference in liquid temperature can be used to make an increase in inlet pressure. A pump

is used to move liquids from one place to another through a piping media. The work done by the pump (W) can be formulated as per Equation (16) [33]

$$W = V(P_2 - P_1) \quad \text{Equation (16)}$$

Fluid enthalpy before pumping (h_1) and after pumping (h_2), where the pump efficiency (η) is 80 %, can be expressed as per Equation (17) [33]

$$h_2 = h_1 - \frac{w}{\eta} \quad \text{Equation (17)}$$

The temperature before entering the evaporator is given by Equation (18) [33]

$$T_w = T_c + W(1 - \frac{1}{\eta})/C_h. \quad \text{Equation (18)}$$

Where: T_c = the temperature of the cold deep seawater (K)

- T_w = the temperature of the warm surface (K)
- C_h = the specific heat of seawater, as 4.186 kJ/kgK

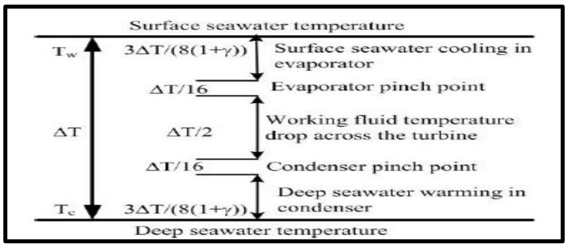
Calculation of the total power of cold and warm seawater pumps (P_{tot}) can be formulated as seen in Equation (19) [33]

$$P_{tot} = 2(9.8Qf\frac{L}{D}\frac{v^2}{2g}) \quad \text{Equation (19)}$$

Where: Q = the water flow rate (m^3)

- f = the friction factor
- L = the pipe length (m)
- D = the pipe diameter (m)
- v = the water velocity in a pipe (m/s)
- g = the earth's gravitational acceleration (m/s^2)

A standard temperature ladder is very important to get the values of T_w and T_c, respectively. Figure 25 shows the model of temperature ladder for calculation of electrical power.



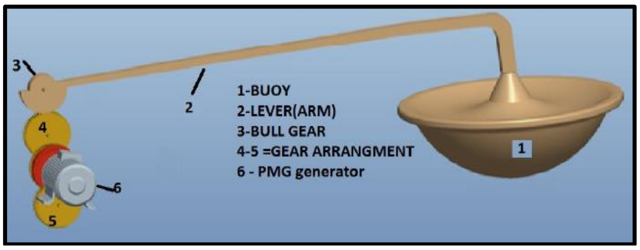


Figure 25: Temperature Ladder Model During OTEC. Figure 26: Components of the Simple and Nonstop Process as Proposed by Nihous (2007) [33]. Buoyant Arm Wave Energy Converter (SAN-BAWEC) [3].

From figure. 25, the gross electrical power (P_g) in OTEC process can be written as seen in Equation (20) [33]

$$P_g = \frac{3\rho C_h Q_{cw} \lambda \varepsilon_{tb} (\Delta T)^2}{16(1+\gamma)T_w} \qquad \text{Equation (20)}$$

Where: ρ is the density of seawater in kg/m^3

- Q_{cw} = the flow rate of the cold water in m^3/s
- γ = the ratio between warm water and cold water
- ε_{tb} = the turbine generator efficiency
- C_h = the specific heat of seawater (4.186 kJ/kgK)
- ΔT = the temperature difference between warm water and cold water (K)

The efficiency of the process is the Carnot efficiency as per Equation (21) [33]

$$\eta = 1 - \frac{T_c}{T_w} \qquad \text{Equation (21)}$$

Harnessing wave energy uses Archimedes principle, the physical principle of buoyancy, as per Equation (22)

$$F_b = -\rho g V \qquad \text{Equation (22)}$$

Where: F_b = the buoyant force

- ρ = the density of the fluid
- g = acceleration due to gravity (m/s^2)
- V = the fluid volume

Figure. 26 shows one of many patented designs for harnessing wave energy. In simple terms, the buoyancy principle states that the buoyant force on a body floating in a liquid or gas is equivalent in magnitude to the weight of the floating object and is opposite in direction; the object neither rises nor sinks. From Fig. 26, the buoy converts the wave energy of ocean into mechanical energy, connected to a lever. The lever converts the mechanical energy into electrical energy. [34] The efficiency of the technology will be governed by the efficiency of the individual components.

All the technologies presented here have efficiency limitations, experience downtime when they need to be maintained and with renewable energy have varying output and availabilities. In short, a 1 MW peak solar photovoltaic plant will not give the full output at which it is rated, taking into account the efficiency of the solar cells, the downtime experienced during the year, the cloudy days and nights when solar energy is unavailable. These factors are summed up in the technology capacity factor. The capacity factor equation can be seen in Equation (23).

$$Average\ Capacity\ Factor\ (CF) = \frac{\sum_{t=1}^{n} E_t}{\sum_{t=1}^{n} P_t} \qquad \text{Equation (23)}$$

Where P = energy production at full rated capacity in kWh

- E = energy production in kWh
- t = time period

- n = number of time periods

From Equation (23), using the time period of a year which is most commonly used for comparisons of plant performance and reliability, we get the following Equation (24):

$$CF = \frac{kWh\ produced\ in\ a\ year\ by\ the\ plant}{kWh\ in\ a\ year\ at\ maximum\ plant\ capacity} \quad \text{Equation (24)}$$

In some energy generation sources, especially renewable energy that is affected by the weather conditions (solar energy, wind energy) the capacity factors vary from country to country than do the capacity factors from other energy generation technologies such as nuclear, natural gas, etc. This means that for example solar PV in Europe will have a lower capacity factor than solar PV in South Africa's northern regions. The technology efficiency of the solar PV plant will also affect the capacity factor e.g. mono-crystalline cell material has a greater output than multi-crystalline cells. Thus, the capacity factor varies for different energy generation technologies based on the following factors:

- Geographical location
- Site conditions
- Technology efficiency and efficiency limitations
- Plant efficiency and plant control philosophies
- Operational efficiency and cleaning of materials
- Maintenance downtime

The capacity factor for various energy generation technologies in the United States (US) and South Africa (SA) can be seen in Table 3. The average capacity factors for solar is lowest.

Table 3: Capacity Factors of Various Energy Sources for the US [35] and SA [36]

Energy Source	US (2019) [35]	SA (2013) [36]	SA (2014) [36]	SA (2015) [36]	SA (2016) [36]	SA (2017) [36]	SA (2018) [36]
Nuclear	93.5%						
Natural Gas	56.8%						
Coal	47.5%						
Hydropower	39.1%						
Wind	34.8%	19%	32%	32%	35%	36%	36%
Solar PV	24.5%	19%	26%	26%	26%	25%	25%
Concentrated Solar Power					31%	32%	38%

Using the equation of the capacity factor of the energy harvesting technologies, which takes into account all the factors affecting the installed technology, Equation (3) can be rewritten per Equation (25)

$$Total\ Available\ Energy\ Potential = \sum(Renewable\ energy\ potential \times CF) + \sum(Energy\ potential\ from\ human\ and\ industrial\ activity \times CF) + \sum(Energy\ potential\ from\ alternative\ less\ carbon\ intensive\ energy\ sources \times CF). \quad \text{Equation (25)}$$

Where: available energy potential is given in kWh/m^2 and for the case of waste to energy, it is given in kWh/m^3.

C. Real Energy Generation Potential

The real energy generation potential of a site is the actual energy generation potential that considers the spatial constraints of the site to accommodate the technologies that generate the energy. Table 4 shows the land use intensity of various energy sources. Renewable energy has a notably significant land use intensity compared to fossil fuel energy.

Table 4: Land use Intensity from Various Energy Sources [Redrawn from [37])

Product	Primary Energy Source		Land Use Intensity (m^2/MWh)				
			US data[a]	US data[b]	EU data[c]	UNEP[d]	Typical[e]
Electricity	Nuclear		0.1	0.1	1.0		0.1
	Natural gas		1.0	0.3	0.1	0.2	0.2
	Coal	Underground	0.6	0.2	0.2		0.2
		Surface (“open-cast”)	8.2	0.2	0.4	15.0	5.0
	Renewables	Wind	1.3	1.0	0.7	0.3	1.0
		Geothermal	5.1		2.5	0.3	2.5
		Hydropower (large dams)	16.9	4.1	3.5	3.3	10
		Solar PV	15.0	0.3	8.7	13.0	10
		Solar CSP	19.3		7.8	14.0	15
		Biomass (from crops)	810	13	450		500
Liquid fuel	Fossil oil		0.6		0.1		0.4
	Biofuels	Corn (maize)	237		220		230
		Sugarcane (from juice)	274		239		250
		Sugarcane (residue)					0.1
		Soybean	296		479		400
		Cellulose, short rotation coppice	565		410		500
		Cellulose, residue			0.1		0.1

[37] Note that data include land use for spacing and from upstream life cycles (e.g. mining). [a]Trainor et al. (2016); [b]Fthenakis and Kim (2009); [c]IINAS (2017); [d]UNEP (2016); [e]Estimate for unspecified region (i.e. generic)

Equation (26) gives the total real energy generation potential of a site including renewable energy, energy sources derived from onsite operational activities and alternative energy sources (less carbon intensive).

$$Total\ Real\ Energy\ Generation\ Potential = \sum(Available\ Energy\ Potential \times total\ area\ available\ for\ energy\ generation) \qquad \text{Equation (26)}$$

Thus, the total real energy generation potential can be written as seen in Equation (27).

$$Total\ Real\ Energy\ Generation\ Potential = \sum(Total\ real\ renewable\ energy\ generation\ potential \times area\ available) + \sum(Total\ real\ energy\ generation\ potential\ from\ human\ and\ industrial\ activity \times area\ available) + \sum(Total\ real\ energy\ generation\ potential\ from\ alternative\ less\ carbon\ intensive\ energy\ sources \times area\ available) \qquad \text{Equation (27)}$$

Where: available energy potential is given in kWh.

Note that waste to energy requires the volume (m^3) and not the area (m^2).

It may be worth noting that all the land on a site cannot be used for all sources. For example, if 100 m^2 is the total area available for solar photovoltaic and solar photovoltaics is adopted, the same 100 m^2 will not be able to be adopted for wind energy by installing wind turbines in this area. Deciding on what energy sources to adopt require further investigation

to provide a comprehensive understanding of the present and future (short, medium and long term views) energy demands of the site, as will be discussed in Principle 2.

2.2 Principle 2: Ascertain the Business' Onsite Energy Needs

A crucial step that is often skipped when a site is planning to incorporate alternative energy sources is to comprehensively understand the site's energy needs. Principle 2 is given as follows; the process flow of Principle 2 can be seen in Figure 27.

Principle 2: Ascertain the site's energy needs, both present and future in the short, medium and long term, consider the following:

- **Type of energy required and their quantities;**
- **Baseload energy requirements;**
- **Fluctuating load energy requirements and its timing; and**
- **Strategies for energy reduction, conservation, load levelling and load shifting techniques and their timing.**

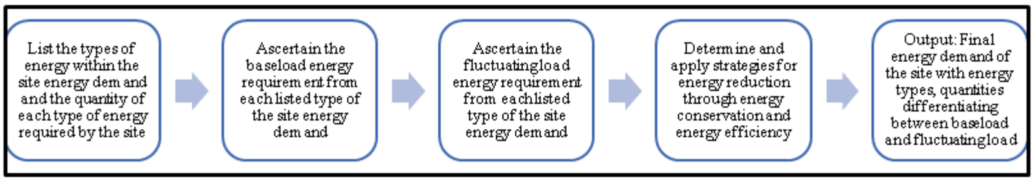


Figure 27: Process Flow for Ascertaining a Site's Energy Needs.

To be able to undertake the process flow in Fig. 27, it is necessary to ask crucial questions about the site's present energy demands such as:

- How much energy does the site use on an hourly or half-hourly basis?
- What drives the energy demand of the site?
- Considering the drivers of the energy demand, can the energy demand be reduced?
- How much of the site's energy use is always required? (baseload)
- How much is the maximum energy demand and what drives the fluctuating energy demand?
- What type of energy demand contributes the baseload energy demand and what technologies drive this demand?
- What type of energy demand contributes the fluctuating energy demand and what technologies drive this demand?
- Can the technologies driving the site's energy demand be more efficient? Determine and apply strategies for energy efficiency and quantify the impact of these strategies in relation to the total energy demand.
- Can the technologies driving the site's energy demand be controlled to serve the need accurately, i.e., no idle time or over-supply? Determine and apply strategies for energy conservation and quantify the impact of these strategies in relation to the total energy demand.

Now that the site's energy demand is optimized, understand the site's future development plans and ascertain the site's future energy demand, if possible, to the stage of full development. Even though the energy demand may not be

accurately quantifiable, if at all, one understands:

- The energy types of the future energy demand, and the
- Typical technologies that will be installed.

This is crucial in the next step of satisfying the energy demand with a low-carbon energy mix.

2.3 Principle 3: Satisfying Business needs Via the Site's Available Resources

With the view of the site's total real energy generation potential and the site's optimized energy demand for both the present and future, the site's energy resources can be matched to satisfy its energy demand using Principle 3. The process flow of Principle 3 can be seen in Fig. 28.

Principle 3: Match the energy sources available to the energy needs of the site considering:

- **Energy efficiency and load dynamics;**
- **Commercial technologies available and their impact, risks and implications for the business; and**
- **Feasibility to install, operate and maintain.**
- **Business imperatives and strategies** (less carbon emissions, insource/outsource strategies, capacity building, corporate social responsibility).

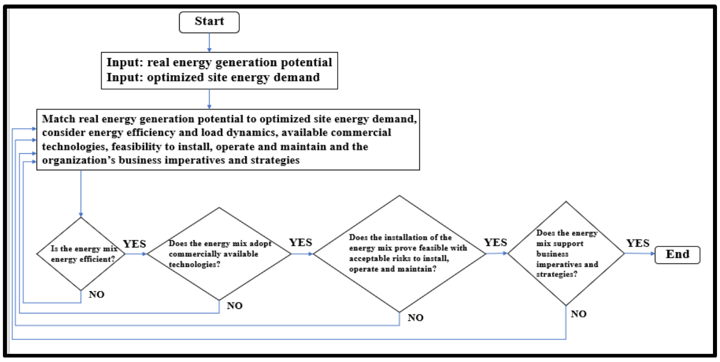


Figure 28: Process Flowchart of Determining a Site's Low-Carbon Energy Mix.

Energy Efficiency and Load Dynamics

Using the principle in [2] for energy efficiency to determine the most energy efficient energy sources to match the energy need, Table 5 lists some common energy needs in commercial and industrial sites energy efficient energy sources.

Table 5: Energy Efficient Sources for Energy need

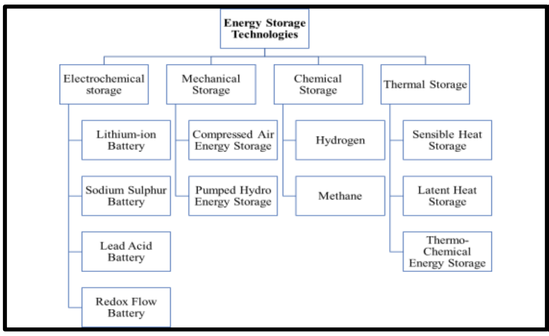
Site Energy Need	Energy Efficient Low Carbon Energy Source
Electricity	• From combustion of fuel such as natural gas (from nearby sources or anaerobic digestion) • Solar photovoltaics • Wind turbines
Heat	• Solar thermal, • Waste heat from other process (such as natural gas, co-generation)
Cooling	• Solar thermal (chillers) • Geothermal (heat sinks)

Motion	• Wind turbines

The energy source(s) supplying the baseload energy demand of the site should be available all the time and the availability of the energy source(s) supplying the fluctuating energy demand should be on demand. Should there be a mismatch between the availability of the energy sources to timeously supply the energy demand, there are two ways to get around this:

- Choose another energy source that fulfils the energy requirement or
- Apply load levelling and load shifting techniques that adopt various energy storage media

It is advisable that another energy source be selected if the load shifting and/or load levelling techniques are unfeasible or if their adoption goes against the strategy of reduced carbon emissions. Load shifting techniques act to store energy for use during another time when energy is not available or is advised not to be used, usually due to cost of peak-time energy. Load levelling techniques act to keep energy consumption constant and use methods such as energy storage to cope with any peak energy demands. This technique is commonly used to maximize the use of the site's notified maximum demand (NMD) with an energy provider. Various energy storage technologies that make load shifting and load levelling possible can be seen in Figure 29.



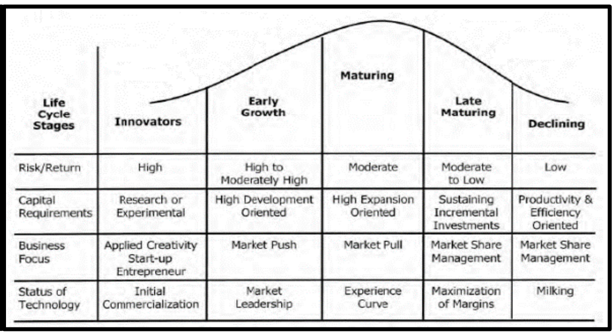


Figure 29: Energy Storage Options (Redrawn from [38]). Figure 30: Life Cycle Analysis of a Technology [39].

Energy storage technologies are adopted to save surplus energy generated by renewable energy technologies and to give a constant power supply of acceptable quality to the site due to the intermittency of renewable energy.

The deciding factors such as the commercial technologies available, their impact, risks and implications on the business will serve to point to the energy sources to be considered for adoption to serve the site's energy demands.

Commercial Technologies Available and their Impact, Risks and Implications for the Business

It is key for developing countries to investigate the energy generation technologies available to their region, more specifically:

- Technology maturity;
- Local footprint of the technology;
- Availability of local markets to supply the technology and spare parts; and
- Availability of skills locally to support the operations and maintenance of the power generation plants.

The aspects above are largely determined from the maturity of the technology in the world. Fig. 30 shows the typical life cycle analysis of a technology. The ‘maturing’ and ‘late maturing’ stages indicate a moderate risk because in these stages, technologies are already well established in the market which will have allowed the skills for their operation and maintenance to penetrate the developing world geographical regions. Established technologies also have much better service offerings in terms of manufacturer guarantees and warranties.

There will also be many market competitors which increases the possibility of securing the energy generation technology at a competitive price.

Feasibility to Install, Operate and Maintain

It is key to establish the financial feasibility of any energy generation technology investment as well as the compatibility of adoption onsite. The financial feasibility will include the cost to install, operate and maintain the energy generation technology. Most trade-offs between the real energy generation potential of each energy generation technology established in Principle 1 matching the site’s optimized energy demand, established in Principle 2 will take place at the feasibility stage. An economic model is key in determining indicators of financial feasibility. A good economic model will typically give the net present value (NPV), internal rate of return (IRR), the nominal payback period and the profitability index (PI). Equation (28) gives the NPV calculation. Equation (29) gives the PI. The IRR is the return (i in Equation 28) when the NPV is zero. The payback period is the amount of time required for cash inflows generated by a project to offset its initial cash outflow.

$$NPV = \sum_{t=0}^{T} \frac{R_t}{(1+i)^t} \qquad \text{Equation (28)}$$

Where: R_t = net cash inflows minus outflows during a single period t

- i = discount rate or return that could be earned
- t = number of time periods

$$PI = \frac{PV\ of\ future\ cash\ flows}{Initial\ Investment} \qquad \text{Equation (29)}$$

The IRR is compared to an organization’s weighted average cost of capital (WACC) rate to determine economic feasibility. When the IRR is greater than the discount rate (or the WACC rate), then the investment is feasible for the business. When the NPV is zero or positive, the investment will pay itself off during its economic lifespan. The payback should be reasonably within the economic lifespan of the investment. The profitability index or PI (given in Equation 3) shows the financial attractiveness of the proposed project and is the ratio of the sum of the present value of the future expected cash flows to the initial investment amount. A PI greater than 1.0 is deemed to be a good investment, with higher values corresponding to more attractive projects. Economic models will differ for each country based on the taxes, penalties, levies, cost of acquiring capital (if not self-funded), incentives offered by the government (if any), etc. The economic model must take into account all applicable factors for the energy generation investment. At this point most energy sources show their financial competitiveness to be adopted by the site and evaluation of the technical compatibility and integration into the site operations must be conducted. It may be that one technology is more financially feasible than another, however, its adoption at the site may have hurdles and limitations.

Business Imperatives and Strategies

It may be that the financial feasibility and technical compatibility to adopt a certain technology may not appear to be as attractive as other energy generation technologies considered by the site, but the organization has a specific interest, imperative, objective or strategy that requires the technology's adoption. At this stage, the organization's overall vision, strategy and the individual departmental strategies must be considered before a final investment decision is made. Noting that certain energy generation technologies will be phased in over a period of 5 to 10 years, the organization's long terms goals may be to adopt certain technologies that may not seem financially feasible or technically compatible for the present but will be in the future with technology maturity and the execution of an organization's long term strategy. At this point the exercise to select a suite of energy generation technologies called a low carbon energy mix, in relation to the impact they will have in serving the site's energy demand, is concluded.

The application of these three principles for achieving energy security has significant implications on business outlook in that:

- Commercial opportunities may be highlighted from looking at a site's ability to generate and sell energy, maximizing company assets, especially land use.
- Commercial opportunities may be highlighted to establish new markets for operations and maintenance of renewable and alternate energy sources.
- Commercialization of knowledge on the establishment of energy generation technologies and a sustainable energy mix especially in developing countries which can be a service offering.

The applications of these principles have the potential to contribute to the profitability of a business as well as increase the human technical capacity and institutional knowledge within a country, creating employment and demand for renewable energy that will ultimately drive the decrease in cost of adopting renewable energy.

3. CONCLUSIONS

This paper has presented three principles for achieving energy security in developing countries. The three principles for achieving energy security provide direction to achieving a low-carbon energy mix by:

- Establishing the 'theoretical energy potential', 'available energy potential' and the 'real energy generation potential' of a site.
- Establishing the optimized site energy demand to be satisfied.
- Efficiently matching the site's energy generation potential to the site's energy demand, considering energy efficiency, load dynamics, available commercial technologies, feasibility and business imperatives.

These principles as the basis for a site to achieve energy security have the potential of making a significant impact on the outlook of a business and brings to light commercial and business opportunities that may contribute to its profitability and efficiency while achieving energy security and environmental sustainability.

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